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AN INVESTIGATION OF THE HEAT TRANSFER CHARACTERISTICS OF THE INDUCTION MOTOR INSIDE THE HERMETIC RECIPROCATING COMPRESSOR

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ABSTRACT

In recent years, environmental concerns and energy consumption become more important. Therefore, compressor manufacturers try to design high-efficiency reciprocating compressors. Owing to developing technology, mechanical, electrical and thermodynamic losses of hermetically sealed compressors are reduced. Nevertheless, the effects of electrical motors are significant phenomena. The thermal behavior of an electrical motor is very important for motor performance, but also has a key role for compressor components heat transfer characteristics.

In this study, heat transfer between the components and the electrical motor of the hermetic reciprocating compressor were investigated theoretically and experimentally. The compressor performance, indicator diagram, motor tests and the detailed temperature measurements of electrical motor and compressor components were given. Analytical model simulations of induction motor and compressor components were performed by using commercial softwares. This part describes analytical models to predict the temperatures of motor and the other parts of hermetic reciprocating compressor. The model simulations allow determining component temperatures with different motor temperatures theoretically. In addition to this, conceptual designs, which have affected the heat transfer on the components and performance of the compressor, were also applied during the study.

The results of the theoretical, analytical and experimental studies are used for investigating the network including conduction, convection and radiation forms of heat transfer inside the compressor. Generated heat transfer network helps to characterize the thermal functions of the main components which leads to the new and better compressor designs.

1. INTRODUCTION

Hermetic reciprocating compressors are the main units of the vapor compression refrigeration systems. These compressors are commonly used due to its smallness and compactness. In recent years, environmental concerns and energy consumption become more important. Therefore, compressor manufacturers try to design high-efficiency reciprocating compressors. Therefore performance improvement studies of the compressor play an important role to reduce overall energy consumption of the refrigerators. Electromotor, thermodynamic and mechanical losses are the main three factors which effect the compressor performance.

The performance of a reciprocating compressor is influenced by the electrical losses. The thermal behavior of an electrical motor is very important for general motor performance, but also has a key role for heat transfer characteristics among compressor components. The electrical losses spread as heat energy inside the compressor housing. Therefore thermal behavior of an electric motor has effects on all components of the compressor. Thermodynamic losses of a hermetic compressor occur due to the heat transfer between the components and pressure losses. It is possible to improve performance of a compressor by investigating the heat transfer analysis. Complex heat transfer network was investigated by using different modeling methods and separating compressor component into simple control volumes. The design of the optimum components influences the efficiency of reciprocating compressors. In order to increase the COP of the compressor an efficient electrical motor design which provides optimum motor performance and minimum loss must be used.

In addition to the theoretical analysis, numerical simulations with engineering software coupled with experimental studies have become an essential development tools in the improvement of performance of reciprocating compressors. Positive efforts have also been made for the complexity of the physical phenomenon inside the compressor ambient. A lot of research work dealing with the use of software coupled with experimental studies as a design tool for various compressor components can be found in the literature. There is also some remarkable research in the development of optimum designs.

Dutra et al (Dutra, 2008) developed a thermal-electrical coupling model and used it to predict the volumetric-isentropic efficiencies and temperature distribution. They used equivalent circuit for steady state model of single phase induction motor. Ooi, presented an analytical study (Ooi, 2003) to improve compressor performance and investigate temperature distribution and heat transfer. In this study 46 control volumes were used and complex geometries simplified. Fagotti et al (Fagotti, 1994) developed a model and focused on the heat transfer from gas to component walls. Working characteristics, without experimental data, were determined. Haas et al (Haas, 2013) presented an investigation that thermal network was studied with 63 control volumes. Simulation results were compared with experimental results. Another study was presented by Oner et al. (Oner, 2009) In this study three phased induction motor was modeled and temperature distribution was investigated by using commercial software.

2. EXPERIMENTAL STUDIES

In order to conduct the electrical analysis and separate compression work from input power for numerical calculation, a pV set-up was built and calorimeter measurements were performed. Piezo-resistive miniature pressure transducers flush mounted in the valve plate were used to measure the pressure inside the cylinder for bearing force investigations. Compression work was done on gas by piston during the compression phase of the compressor. The gas force on piston creates reaction forces on crankshaft bearings. These reaction forces must be carried in the bearings by the oil film pressure. For the determination of the cylinder volume an optical encoder was placed on the shaft, from which the position of the shaft can be determined. From the position of the shaft the piston position was calculated and also the momentary cylinder volume. pV measurements were conducted at ASHRAE test conditions (Condensing temperature:54.4 °C, Evaporating temperature: -23.3 °C) to examine the pressure characteristics of the investigated compressor. The results of pV measurements of the reciprocating compressor are shown in Figure 1.

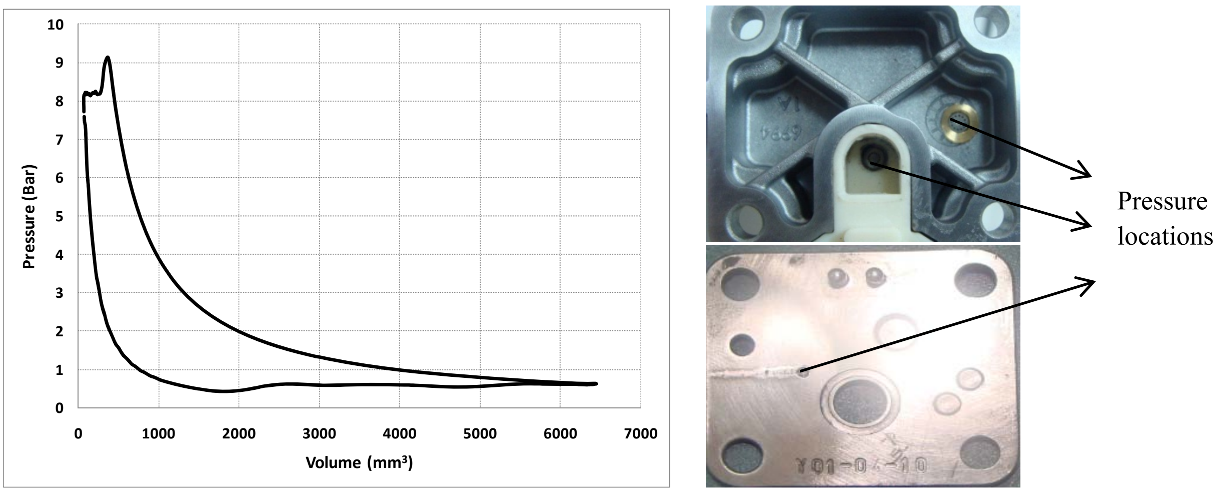


Figure 1: pV-diagram and temperature/pressure measurement locations

Furthermore detailed temperature measurements were also done at various points inside the compressor. Temperature measurement points were given in Table 1 55 thermocouples were mounted on the compressor components walls and flow lines. Besides, 40 thermocouples were used to get single phase induction motor temperatures when calorimeter measurements were performing. Baseline temperatures were collected to compare simulation results. In order to get motor efficiency and working characteristics motor-test system was used. Motor-test system provides torque, speed, power, current, voltage datas for different working conditions.

Table 1. Temperature measurement points

No	Measurement Point	Number	No	Measurement Point	Number
1	Lubrication Oil	4	10	Cylinder Head	2
2	Suction Muffler Backside	4	11	Discharge Muffler	2
3	Suction Muffler Front side	4	12	Discharge Tube Inlet	1
4	Inner Gas	6	13	Discharge Tube Outlet	1
5	Cylinder Surface	4	14	Shell	10
6	Body	8	15	Compressor Outlet.	2
7	Discharge Plenum	2	16	Suction Muffler Inlet	1
8	Compressor Inlet	2	17	Suction Muffler Outlet	1
9	Suction Plenum	1	18	Electrical Motor *	40
Total:95					

No	Measurement Point	Number	No	Measurement Point	Number
1	Stator Lamination-Left	9	9	Upper Windings- Left	1
2	Stator Lamination-Right	9	10	Upper Windings -Right	1
3	Stator Lamination-Back	7	11	Upper Windings -Back	1
4	Stator Lamination-Front	7	12	Upper Windings -Front	1
5	Lower Windings- Left	1			
6	Lower Windings -Right	1			
7	Lower Windings -Back	1			
8	Lower Windings -Front	1			
*Electrical Motor	Total:40				

3. NUMERICAL ANALYSIS

Analytical models were studied with commercial engineering software. At first, numerical model of the induction motor was used to compare torque results. Numerical model is in good agreement with experimental results. In order to obtain thermal model for induction motor numerical model was imported to commercial engineering software which is dedicated to the electromagnetic performance of motors and the optimization of their thermal calculations. The model is given in Figure 3. The geometric values were edited and external environment of motor was modeled for the conditions like the inside of hermetic compressor housing.
The gas around the motor was modeled as R600a (isobutane) refrigerant and speed was edited at running speed range that the load of induction motor of hermetic compressor which run for ASHRAE condition. The housing was not used and the temperature of the gas was edited as experimental value.

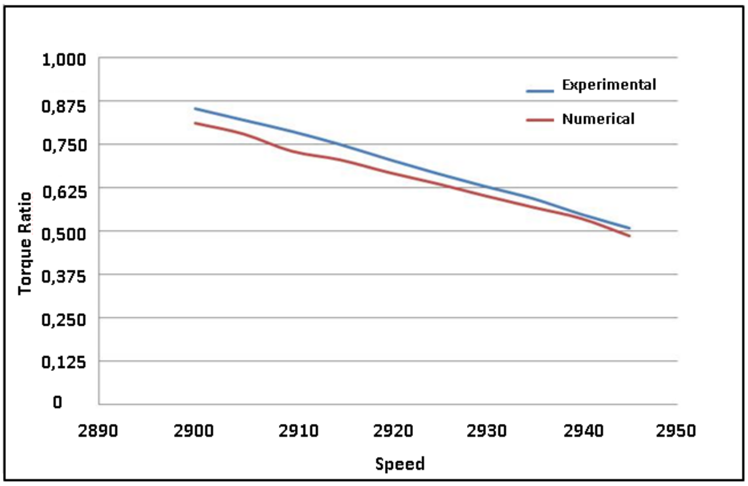


Figure 2: Comparison of the experimental and the numerical results of torque ratio

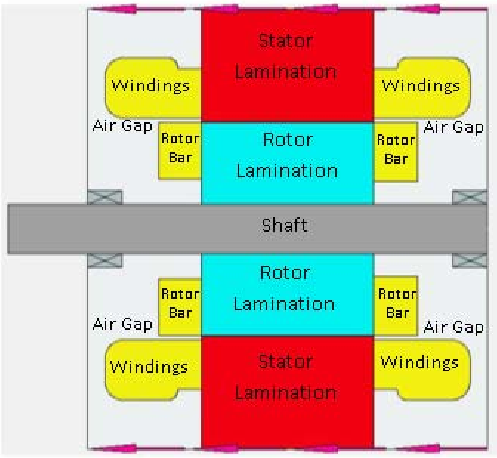


Figure 3 : Simulation model

Schematic thermal network is given in Figure 4. Symbols for Figure 4 explained in Table 2. It shows thermal resistances, interfaces, losses; conduction, convection, radiation heat transfer mechanisms.

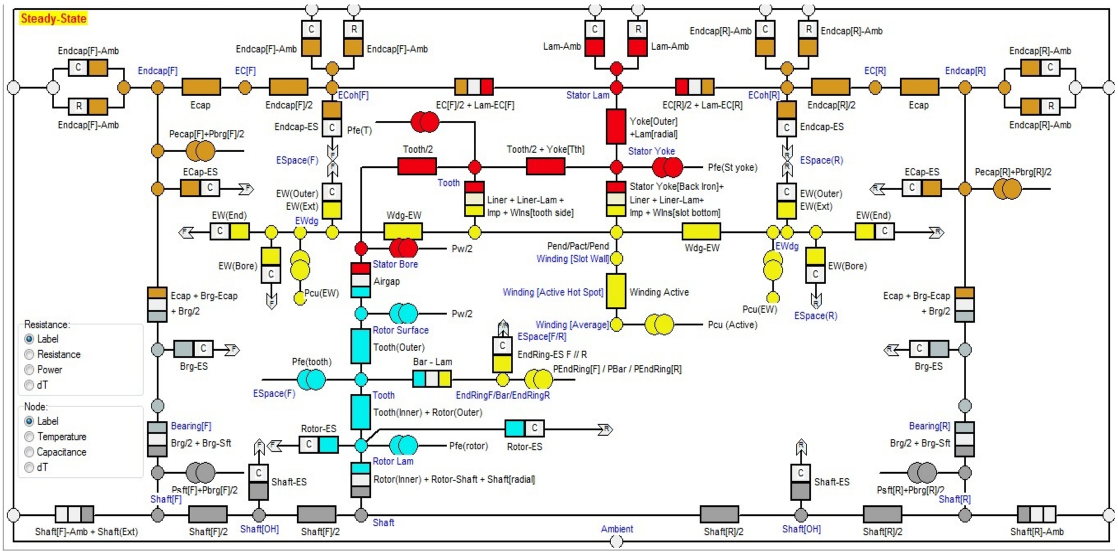
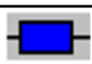


Figure 4: Thermal Network model

Table 2. Symbols for thermal network model

Symbol	Information
	Termal Resistant
	Interface Resistant
	Convection
	Radiation
	Loss
	Connection Point

After modeling induction motor for baseline design, the motor cooling methods were used on this model. Spiral water jacket, axial water jacket, spray cooling models were simulated for steady state conditions and according to the parameters temperature changes were investigated.

In addition to analytical models for induction motor, other hermetic compressor components were also studied. Compressor divided into 12 lumped element and energy balance equations were applied to all control volumes. Figure 5 shows these lumped elements: Suction muffler 1st volume, suction muffler channel, suction muffler 2nd volume, suction plenum, cylinder, discharge plenum, discharge pipe, housing, oil, internal environment, body and motor. All suction line and discharge line pressures were taken 0,624 bar and 7,61 bar respectively. Complex geometries were simplified and correlations from the heat transfer network of the compressor (Ozdemir, 2007) were applied. Figure 6 shows solution method for analytical model of lumped parameter method. Simulation starts with geometrical, electrical parameters, operating conditions and initial temperatures. After that step, procedure continuous with calculating fluid properties (dynamic viscosity μ,kinematic viscosity ν,density ρ,specific heat cp,enthalpy h, kinetic energy of turbulance k) for every loop. Energy balances are applied for many times until internal environment temperature converge for all elements. Chart shows suction muffler inlet (T_{in}), 1st volume (T_{sm1}), channel (T_{ch}) and 2nd volume (T_{sm2}); suction plenum (T_{sp}), discharge plenum (T_{dp}), discharge muffler (T_{dm}), discharge pipe (T_{dpip}) compressor outlet (T_{out}) temperatures respectively.

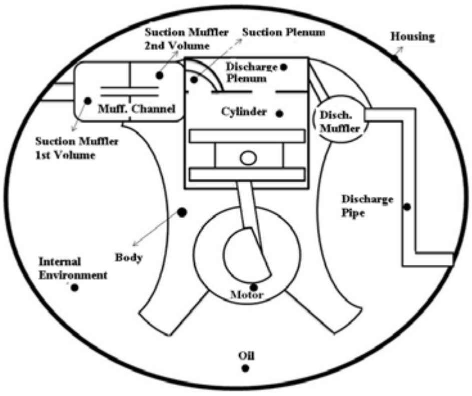


Figure 5: Compressor lumped elements

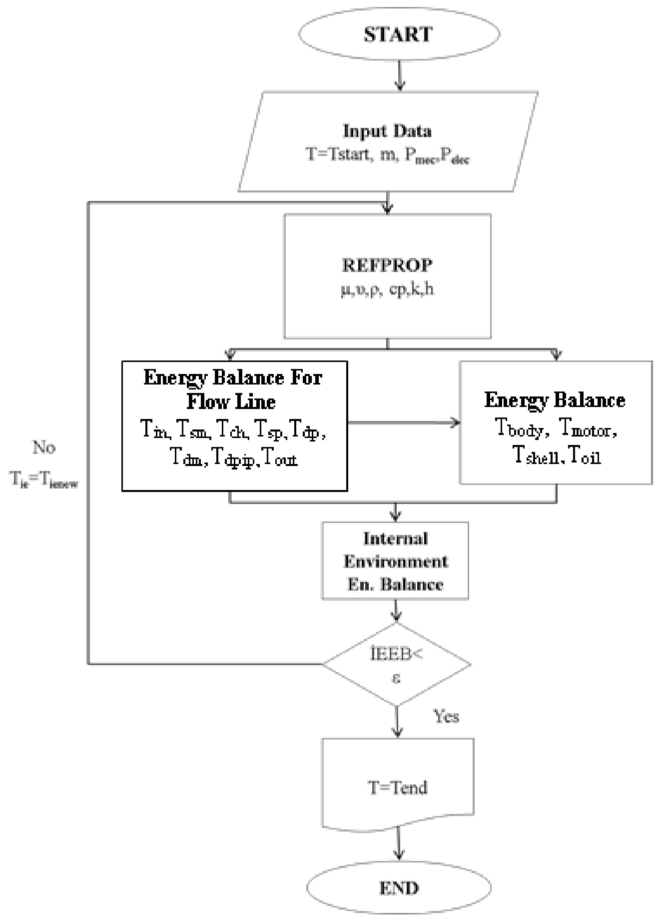


Figure 6: Model algorithm

4. RESULTS AND DISCUSSIONS

The results of experimental studies show that motor losses have significant importance for hermetic compressor performance. Results of compressor performance, indicator diagram, motor tests and the detailed temperature measurements of compressor components proved that the changes in temperature impacts overall performance and losses. Detailed temperature measurements of induction motor are given in Figure 7. It can be easily examined that temperature distribution is nearly homogenous. Average temperature of stator lamination 74,6 °C and there is not remarkable temperature difference between all sides. Average end winding temperature is 74,4 °C. It can be observed from front and back views, due to oil in crankcase, bottom end windings are cooler than upper windings.

Figure 7: Detailed temperature measurements of induction motor (°C)

Simulation results for baseline model were given in Figure 8. The results are in a good agreement with experimental measurements. There is approximately 3K temperature difference possibly due to unidentified dynamic effects of oil flow over the electrical motor in the model. Simulation results give opportunity to see temperatures of motionless parts of induction motor. Furthermore moving component's temperature distribution which is impossible to measure by thermocouples can be easily found.

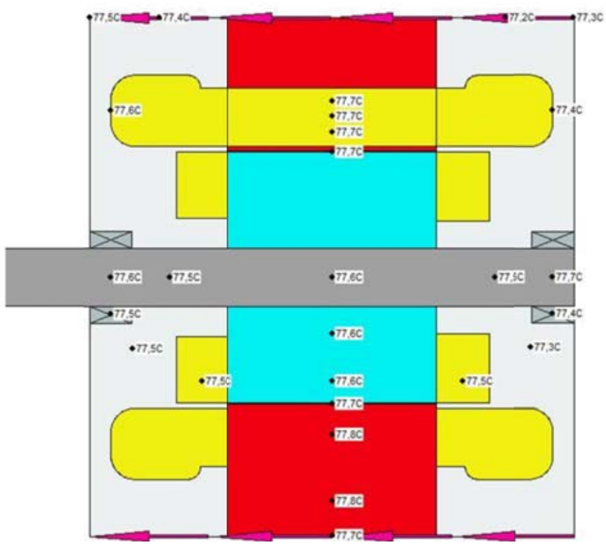


Figure 8: Temperature distribution for simulation model

In simulations temperature measurement points on the electrical motor is divided to different sections. These sections are summarized as front electrical wiring (ew-fr), average electrical wiring (w), stator lamination (slam), stator surface (ssur), rotor surface (rsur),rotor teeth (rteeth), rotor lamination (rlam), rotor bars (rbar), Shaft center (shft), back electrical wiring (ew-bck).

Alternative cooling methods for motor investigated in this study. Spray cooling model simulation results are given in Figure 9. In this cooling method end windings are cooled by oil passing from down to up of crankshaft channel. Inlet temperature was edited 65 °C constant, temperatures all over the motor laminations and windings decreased approximately 6-7 °K.

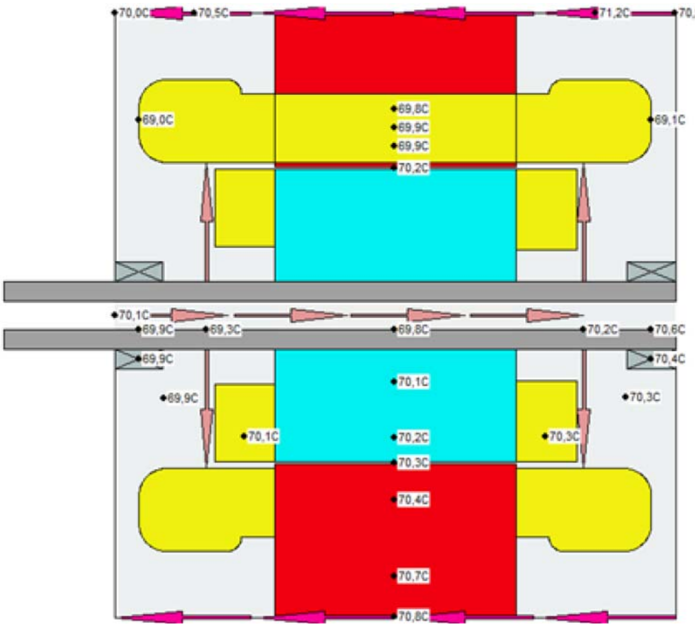


Figure 9: Temperature distribution for simulation model

Spiral water jacked model simulation results are given in Figure 10. In this model, there is a helical channel around stator lamination packet. The fluid inside the channel was modeled as water. Furthermore fluid properties can be set at fixed values and new fluids can be created. For the results which are given below, first, inlet temperature of fluid and channel width were set 32,2°C respectively. For these conditions temperatures were predicted for different flow rates. For constant channel width, simulation results show that, for 1.10^{-7} m^3 flow rate temperature distribution is homogenous. Flow rate from 1.10^{-7} m^3/s to 8.10^{-7} m^3/s decreases the temperatures respectively and homogenous temperature characteristic of induction motor become different.

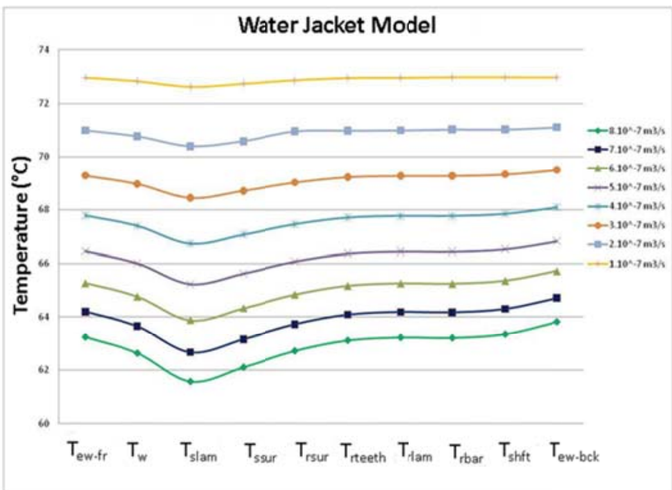


Figure 10: Spiral water jacked model simulation results

In Figure 11 axial water jacket model simulation results are given. For this model, fluid follows axial channels to cool motor lamination. Flow rate is critical parameter. Results show that, motor temperatures decrease for high flow rates.

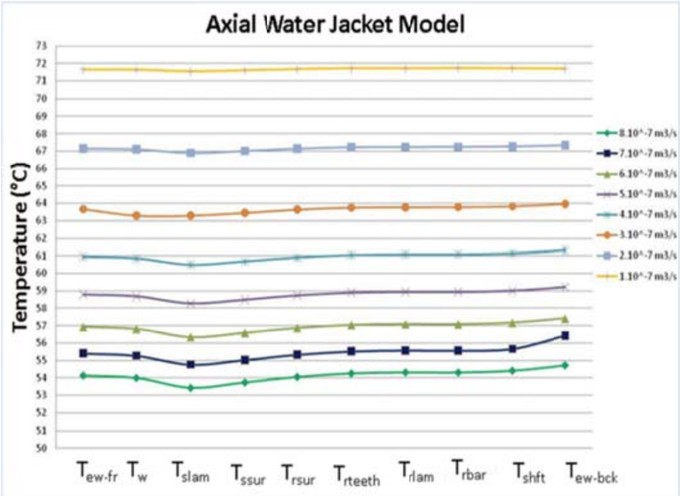


Figure 11: Axial water jacket model simulation results

In addition to the electrical motor's detailed thermal analysis, heat transfer processes between the components of a hermetic reciprocating compressor were also studied. The results of lumped parameter method analytical model for compressor flow line and components are given in Figure 12. According to the temperature results, it can be seen that, flow line and wall temperatures are in a good agreement with experimental measurements. Chart shows suction muffler inlet (T_{in}), 1st volume (T_{sm1}), channel (T_{ch}) and 2nd volume (T_{sm2}); suction plenum (T_{sp}), discharge plenum (T_{dp}), discharge muffler (T_{dp}), discharge pipe (T_{dp}) compressor outlet (T_{out}) temperatures respectively. The other temperatures are summarized as oil (T_{oil}), internal environment (T_{ie}), compressor body (T_{bdy}) and compressor shell (T_h).

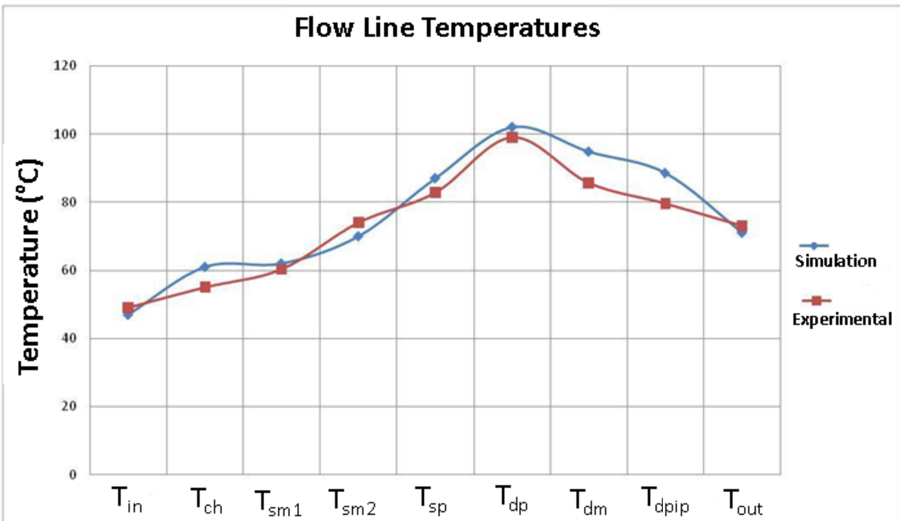


Figure 12: Lumped parameter method analytical model simulation results

General temperatures for different average electrical motor temperatures are given in Figure13 & Figure14. Simulation results show that motor temperatures affect all components directly and they are all dependent motor losses. Decreasing the average temperature of induction motor affects component temperatures. It decreases general temperatures all over the compressor.

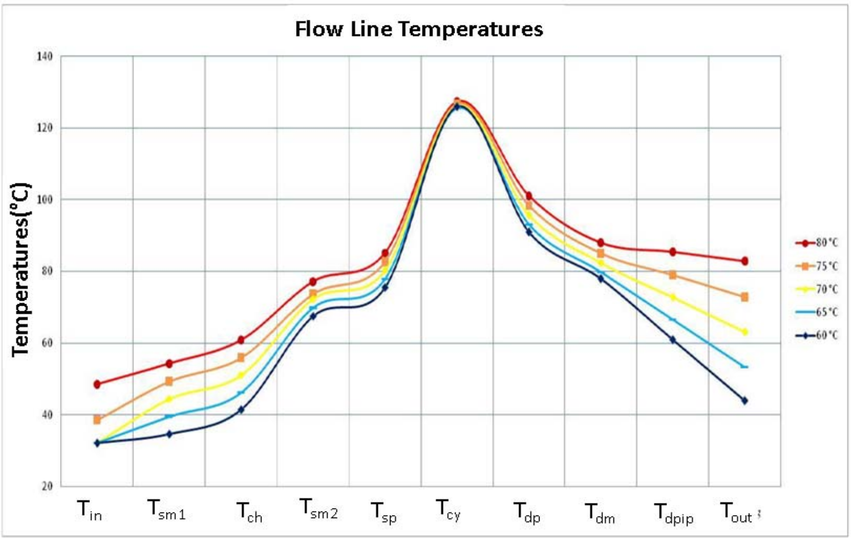


Figure 13: Predicted temperatures for different motor temperature (1)

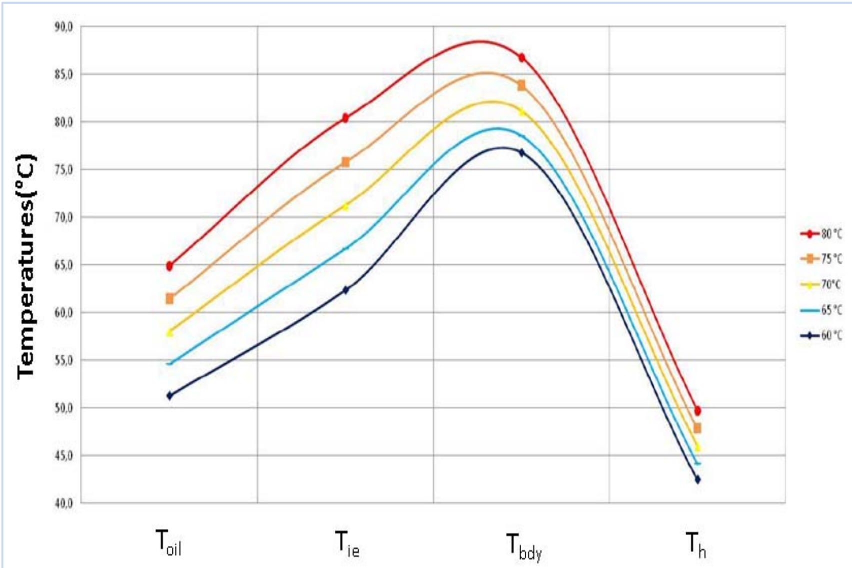


Figure 14: Predicted temperatures for different motor temperature (2)

5. CONCLUSIONS

In this paper, heat transfer between the components and the electrical motor of the hermetic reciprocating compressor were investigated theoretically, numerically and experimentally. The compressor performance, indicator diagram, motor tests and the detailed temperature measurements of electrical motor and compressor components were given. Analytical model simulations of induction motor and compressor components were performed by using commercial software.

- The results of measurements and simulations show that, motor temperatures are nearly homogenous. due to oil in crankcase bottom end windings are cooler than upper windings.
- According to cooling methods motor temperatures can be reduced for different rates. In water jacket applications when flow rate increases, homogenous temperature characteristic of the motor changes.
- According to lumped parameter model that was applied compressor components, motor temperatures directly affect all over the compressor.

The results of the theoretical, analytical and experimental studies are used for investigating the network including conduction, convection and radiation forms of heat transfer inside the compressor. Generated heat transfer network helps to characterize the thermal functions of the main components which leads to the new and better compressor designs.

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